DEPARTMENT OF THE AIR FORCE
OFFICE OF THE SECRETARY

MEMORANDUM

This a study done by EK for Dr Charyk a couple of years ago. It has been brought up to date at least once and copies are enclosed. It is as good a set of parametric numbers as I have obtained. You may keep if you like. If not, I think Buss might want them, although I have not asked him.

H13-B-3

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GENERAL STUDY OF
AERIAL PHOTOGRAPHIC INSTRUMENTATION

Prepared by
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Rochester 4, New York

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GENERAL STUDY OF AERIAL PHOTOGRAPHIC INSTRUMENTATION

During the past several years there have been significant advances in the design and manufacture of large, high-performance optical systems for aerial reconnaissance. Furthermore, fine-grain, high-definition films have been made with sufficient sensitivity to be used with these new lenses. Accompanying these gains, a more complete understanding of image formation has made it possible to predict performance with reasonable precision and to design with assurance.

It seems worthwhile to review these advances in the state-of-the-art in a general and theoretical way. By this means the basic physical limitations can be sorted out from those which represent our level of progress and understanding and it will be possible to judge intelligently what areas of concentrated effort will yield the greatest advancement.

The charts which follow cover the highlights of a rather general but limited study of the instrumentation for photographic reconnaissance. The study is general in that the optical, photographic, and mechanical parameters are treated in a fundamental way and an optimum relationship is obtained for a given set of conditions. A limitation exists in that the only measure of output

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is angular and ground resolution to determine quality and total coverage to measure quantity. To make the numbers more meaningful, this output is frequently given in terms of ground resolution and coverage from a satellite at an altitude of 100 n mi. Although this is restrictive, the numbers can easily be transposed and applied to almost any vehicle.

It must be realized that the area of study is quite broad and that many of the details are omitted for the sake of brevity and generality. Although the information given here is representative the quantitative results should not be considered highly precise since small deviations in the data incorporated in the study had to be averaged in order to represent the general case. Furthermore, a different design philosophy than that presented here can result in better performance in certain areas at the expense of poorer performance in others. For example, the emphasis will be placed on good resolution with adequate coverage. But if the coverage is severely reduced, the resolution can be further improved.

From this point on, the text will expand upon the charts that follow.

Chart 1 - General Study of Camera Systems for Photographic Aerial Reconnaissance.

The purpose of the study is to investigate the trade-offs among the many parameters applying to this field and to optimize the photographic output for a given set of conditions. After this is done it is possible to determine what conditions must be met to obtain a specified performance level, and finally, the areas of which may yield the greatest advances can be predicted.

The parameters and conditions can be divided into three categories. The first are those which describe the natural limitations imposed by the sun, the atmosphere, the earth, and the wave nature of light. Although man has no control over these natural conditions, he has certain choices such as spectral region and time of day.

A second category contains parameters which are usually specified to the designer of the camera system. The required photographic output and vehicle characteristics fall in this class. The third group of parameters are those which are usually left to the choice of the camera designer. Obviously, the distinction between the second and third categories is not absolute but is given for convenience to determine the trade-offs that exist between the camera system, vehicle, and program requirements. For example, errors in vehicle angular motion and position may be controlled adequately by the vehicle attitude control system and ground tracking. But if the residual errors are out of bound, the camera system can include a V/H sensor. Those variables in the hands of the camera system designers are limited by the state-of-the-art and it is this limitation that will be studied to determine an optimum solution for a given set of circumstances.

Chart 2 (page 3) - Optimum Spectral Region for Aerial Photography.

These factors which primarily influence the choice of spectral region are listed on the chart. They combine in such a way to eliminate, for all but very special applications, the ultra violet below about 0.3 microns and the infrared beyond about 0.9 microns. In the ultra violet, atmospheric transmission is the principal deterrant but relatively low solar energy and low scene reflectance and contrast also reduce the desirability of this region. Solar irradiance, atmospheric transmission, scene reflectance and contrast all rise quite rapidly in the region above 0.3 microns but are hardly adequate until 0.4 microns is reached. Beyond about 0.9 microns, inadequate photographic sensitivity is accompanied by falling solar engergy. Therefore the optimum region must exist somewhere between 0.4 and 0.9 microns.

Since the available energy is a fundamental limitation it seems obvious to include as large a spectral region as possible. However, the scene contrast changes character quite markedly beyond about 0.7 microns. This is due primarily but not solely to the high infra red reflectivity of chlorophyl. In fact, it is possible to reduce apparent scene contrast by combining a certain proportion of visible and infra red light. To avoid this, the visible and infra red should be treated as separate regions although the boundry between them is not sharp. The peculiar brightness relationships in the scene viewed in the infra red make this region ideal for special purpose photography such as camouflage detection. It is probably not advisable to use infra red for general purpose photography since the diffraction of light and the film sensitivity tend to reduce resolution in the infra red compared with the visible. Existing infra-red-sensitive films are more grainy than panchromatic films of the same level of sensitivity. An ideal situation is to use both panchromatic film for maximum resolution and infra red for special detection.

In the visible region (approximately 0.4 to 0.7 microns) the apparent scene contrast rises from blue to red. This is due to scene reflectance as well as haze. As a result, it has been common practice to eliminate the blue with a yellow filter. But the decision to eliminate the blue has been strongly influenced by the inadequate color correction of lenses commonly used in aerial photography. It appears to be inherently wasteful to eliminate the blue region where the solar energy is at its peak, where photographic films generally have high sensitivity and where diffraction effects are minimized. Furthermore, the apparent gain in scene contrast if the blue is eliminated may not be equivalent to a gain in information. The contrast is enhanced at the expense of eliminating nearly all the light from the shadow regions which receive their illumination from the blue sky. Therefore, the higher contrast gives an apparent increase in picture sharpness but not necessarily in information content.

Another potential gain, in addition to the elimination of the yellow filter, is an extension of the red sensitivity of aerial films. If this extension be kept small to avoid large changes in brightness relationships, there will be a modest but useful increase in available energy.

For the remainder of this study, it will be assumed that as much of the visible spectrum will be used as the optical correction of the lens and the spectral sensitivity of the film permit.

Chart 3 (page 2) - Altitude.

It was stated previously that the quantative results of this study can be applied to almost any altitude and vehicle. The parameters associated with altitude are indicated very briefly on Chart 3. Larger coverage is obtained with an increase in altitude but there is potentially better resolution at lower levels. For satellites at high altitudes the radiation belts become a hazzard. At altitudes much below 100 nautical miles, atmospheric drag reduces life time, causes heating and, at very low levels, turbulent air flow. Although the ground resolution is potentially higher at low altitudes, the camera must compensate for a higher velocity to height ratio, V/H, and resolution is endangered by image smear.

The aircraft region extends from the ground upward to about 20 miles. Above this sustaining lift becomes difficult to achieve without a high velocity which can cause excessive heating and air turbulence.

Therefore, there is a region between aircraft and satellite altitude which is difficult to exploit. Undoubtedly there is no substitute for getting close to the object in order to improve the resolution and so, for this study, which is slanted toward satellites, an altitude of 100 nautical miles will be assumed.

Chart 4 - Resolution vs Field Angle

The level of achievement in lens design and manufacture is indicated in Chart 4 where resolution (quality) is plotted against field angle (quantity). To provide a meaningful criterion, the quality is given in terms of angular resolution of the lens plus film for the finest grain aerial film available and for a low contrast (2:1) Mil Std chart. Perhaps a better understanding of angular resolution and field angle can be obtained from the additional coordinates giving ground resolution and coverage from 100 miles.

Obviously, the better resolution is represented by a lower number on the chart. Consequently, the direction to move to obtain higher performance is toward the lower right-hand corner of the chart.

Resolution is given for several representatively good lenses in the form of a line extending from maximum quality (lower end of the line) at the center of the field to minimum quality generally at the edge of the field. For comparison, the resolution if the lens were truely diffraction limited is given by a triangle. The lenses listed span the wide range from the short-focus, wide-angle Biogon to the long-focus, narrow angle G lens. It is interesting that most of the lenses fit on a straight line and this line indicates the price that must be paid in smaller field for improvement in angular resolution.

A notable exception in the 24 inch f/5.6 lens designed by Pacific Optical for the Wright Field high acutiy program. This lens has about twice the expected field for its measured resolution. Some lens data are either proposed or assumed and these lenses are represented by a dashed line. Incidentally, even though these lenses are all of similar form, in that they are of about the same f/No. and quality compared to the diffraction limit, it is interesting to note that the 6-inch Metrogon with Super XX film and even the f/1 Baker-Nunn satellite tracking camer match the curve quite well.

Note that all these lenses, which represent the best in the state of the art, are near the diffraction limit and have a resolution range from center to edge of the field of about two or less. This data was averaged and representative modulation transfer curves were drawn for the center and edge of the field. These curves, plus the relationship between field and resolution, are used in the remainder of this study to portray the existing limit in lens design and manufacture. Although the data does not take into account such details as light transmission or color correction, the light efficiency is relatively constant for the entire range of lenses. The short-focus, wide-angle refracting lenses generally have poorer color correction and require heavier filtering than the long-focus, narrow-angle reflecting systems. But these reflecting systems generally have lower transmission due to obstructed apertures and reflection losses.

An effective way to increase the field of a camera with little loss in quality is to use a panoramic approach. Several panoramic systems, illustrated on Chart 4, again fall on a nearly straight line. The line position indicates a gain of about five in quantity for the same quality. Obviously, there must be an increase in weight if the lens is used in a panoramic system but this weight increase is far less than the factor of five required for an array of five non-panoramic cameras. The line defining the quality and quantity of panoramic systems is probably less sharp than that describing the lenses alone. The angle of panning is limited due to image smear by sweep rate and cycle time. It can be larger for lower V/H and depends greatly on the quality of mechanical design in the camera. There are exceptions to the rule such as E-5. This system has a smaller field than expected probably because the field of the lens itself is quite small.

Chart 5 - Ideal Correction of Image Smear.

The effects of image smear must now be added to the resolution of the lens and film to obtain the image quality of the camera system. Image smear not only includes the residual errors in image motion compensation but also the instability of the vehicle and the vibration within the camera. There are several sources of error which cause smear and these are not limited to the direction of motion of the vehicle. In Chart 4 the smear is given for each error source, in the two component directions, and for typical strip and frame cameras. The assumed altitude of a circular orbit is 100 nautical miles for which V/H is 0.05 radians per second. Errors are given in terms of this V/H and the total in terms of angular rate. The magnitude of the error source represents approximately the best that can be done at this time with present techniques. In fact, it is estimated that it will be difficult to make great improvements at low satellite altitudes unless there are some major changes in method. To be sure, at higher altitudes where V/H is less, the smear rate, in terms of radians per second, may be reduced, but the longer lever arm of altitude will probably more than compensate for the reduced smear rate.

Attitude, for example, is quoted at 0.2° about each of the three axes. Sensors are being designed to detect 0.1° with respect to the apparent horizon but it is assumed here that in implementing control, the error will be doubled. Excellent image motion compensation seems to require a V/H sensor. Although some sensors are being designed to approach 0.1% accuracy, cloud interference, loss of signal over featureless terrain, finite time constant, and noise influence the interpretation of the signal and add to the difficulty of making the camera follow the signal precisely. Therefore, an error of 0.5% was chosen for the sensor--camera drive combination.

The errors vary in time and direction and are relatively independent. Therefore, they can be added as a root-sum-square in the two directions. Two ellipses at the bottom of the chart are polar plots of these net errors for the two camera types. Note that although the two cameras have different individual errors the mean error in both cases is very nearly 1%. Consequently, 1% of V/H at 100 miles or 1/2 milliradian per second will be considered an ideal correction of image smear.

Chart 6 - Examples of Residual Smear Rate. To substantiate this choice of 1/2 mr/sec for the probable smear limit, several examples are given in Chart 6. E-2 was a very quiet strip camera at a high altitude of 300 miles. The budgeted smear was .76 mr/sec at the center of the field and a greater amount off-axis. E-6 is a panoramic system which is mechanically much more active. With conservatism the budgeted smear was placed at 2.64 mr/sec. [redacted]

Chart 7 - Angular and Ground Resolution for Fixed Input to Camera Lens.

The effects of image smear can now be included in the lens film resolution. For the sake of orderliness only one variable will be treated at a time. At first lens diameter and angular rate of smear will both be fixed. This in effect fixes the input to the camera lens. The lens diameter determines the amount of light energy entering the optics and determines the diffraction limit in terms of object space. Incidentally, a fixed lens diameter has practical significance in that the weight of the lens is primarily dependent on its diameter rather than any other characteristic.

The variables, which will be treated one at a time, are focal length and film. Since the lens diameter is fixed the f number is obviously related directly to focal length. Exposure must then be adjusted to match the film and f number.

The results of varying the focal length can be measured in terms of angular or ground resolution as indicated in the graph on Chart 7. Obviously better quality is associated with a smaller angular resolution and, therefore, with a lower position on the graph. Angular resolution varies as indicated and goes through a minimum at what may be termed an optimum focal length. At a shorter focal length the exposure time is reduced because at the small f number image smear becomes negligible. However, the scale of the image is very small and the film resolution becomes the limiting factor. This is indicated on the graph by a line describing the film limit which is related to the scale of the picture. If the focal length is too long, the exposure time must be increased due to the high f number. Consequently, image smear becomes the limiting factor and the large image scale does not tax the resolution of the film. This is indicated on the graph by a line labelled smear limit. The combination of film resolution and image smear give the curve, as indicated, with optimum quality of output at some particular focal length. In conclusion, there is some optimum focal length for a fixed lens diameter and image smear rate and for a particular film.

Chart 8 - Angular Resolution vs Focal Length for Various Films.

The type of curve illustrated in Figure 7 is given for several films in Figure 8. In this case the fixed input is a 10-inch lens diameter and 2 milliradians per second smear rate. The choice of numbers is not restrictive in that the only intent here is to compare 3 films under identical situations. Incidentally, these numbers are rather similar to the characteristics of E-6.

Each curve passes through a minimum or optimum as was indicated on Chart 7. The fine grain film is associated with an optimum focal length of about 40 inches and produces a resolution in the image of about 110 lines per millimeter. The coarsor grained films yield optimum output at longer focal lengths as would be expected because their greater speeds can make use of slower lenses but greater image scale is needed to compensate for their coarser grain. It is a very significant result that all three curves have a minimum at about the same level of 2 arc seconds. For comparison the output of a lens accompanied by Tri-X Aericon was calculated and at a rather large focal length the resolution was again approximately 2 arc seconds. From this one can conclude that the quality of output is relatively independent of the film under the conditions of a fixed input to the camera lens, provided the focal length is optimized for the film and conditions under which the photography is taken.

One obvious reason for the equal equivalent quality of the films mentioned is that these films are all of the same family, having approximately the same spectral sensitivity and gamma and processing. If there is to be a gain in the state of the art of film manufacture, the curve for that improved film must dip down to a lower level on the graph shown. There is good reason to believe that such a gain is in the offing.

Chart 9 - Comparison of Systems Using Different Films. From Chart 8 it was concluded that the relative ground and angular resolution is the same for the three emulsions. In the table in Chart 9, the differences are only 7 and 8 percent which is less than one increment on a standard resolution chart, but the resolution in the image must be considerably better in the fine grain emulsion compared with the coarser grain emulsions. This can raise problems in duplicating the image for distribution to the intelligence community. Focal length is shorter for the finer grained film which may lead to more compactness in the lens, however, the relative aperture must be greater, that is, the f number must be smaller, and this can lead to problems in lens design. If, for example, a still finer grained film than SO-132 is devised, the f number may be impossibly small for the lens designer and some sacrifice in resolution will result. This is illustrated in Chart 8 by the dashed lines near f/2.8. The large advantage of the fine grain film is in the small amount of material needed for a fixed amount of coverage. Film area and weight increase as the square of the focal length and, therefore, eight times less SO-132 film would be required for the same coverage than the amount of SO-130 film. Still another advantage of the fine grain film is its relative insensitivity to radiation. From these statements one can conclude that it is best to use as fine a grain film as possible and the limitation here exists only in the lens design of a short enough focal length lens and in the problem of reproducing fine image resolution.

Chart 10 - Effect on Image Smear.

The next parameter to vary is image smear. Chart 10 illustrates the effect of various amounts of smear rate when angular resolution is plotted against focal length. In this case the fixed conditions are a 10-inch diameter in SO-132 film. This family of curves indicates that a reduction in smear rate is accompanied by a pan improvement in the angular resolution and also by a shift in the optimum focal length. The improvement in angular resolution is about 25 percent for a factor of 2 reduction in smear rate. Obviously, this improvement cannot go on indefinitely, since the lens diameter limits the resolution to about 1/2 arc second. Consequently, further improvement yields smaller and smaller gains until the angular resolution reaches 1/2 of arc second asymptotically.

It is an important conclusion that a change in the smear rate changes the optimum focal length. To take full advantage of an improvement one must also increase the focal length. However, the minimum on each curve is relatively broad and can be defined by a region describing the optimum f number and focal length. If one considers a range of smear and illumination, the resulting range in angular resolution can be minimized if the focal length is slightly shorter than the optimum for the nominal case.

From this point on in the study, it will be assumed that every camera design will be an optimum design in that the optimum focal length will be chosen for each set of conditions. As a result the only information required is the line in Chart 10 which describes the optimum focal length for a given condition.

Chart 11 - Ground Resolution vs Aperture for a Given Smear Rate. The next parameter to be considered is lens diameter. It is plotted in the graph against angular resolution for the optimum focal length with smear rate as a parameter. Resolution is also given in terms of ground resolution from 100 nautical miles. These data are independent of the film for the current series of aerial films. This is true because all of these films give approximately the same angular resolution if the focal length is optimized.

Obviously the resolution is improved, that is the number is reduced, if either the lens diameter is increased or smear rate is reduced. Notice that the rate of improvement in resolution with an increase in lens diameter is not one to one. If the diameter i increased tenfold, the improvement in resolution is only about 5 or 5 times.

It was estimated previously that a smear rate of 1/2 milliradian per second is approximately the practial limit for photography from a satellite at a 100 nautical miles. The line representing this smear rate is in red to call attention to this practical limit.

It is now possible to use a few examples to determine what is required to obtain a given amount of resolution. A goal that seems to be in the minds of many is a [redacted] Although there are no fundamental limits on lens diameter this conclusion is quite overwhelming. Even if someone were to claim that he could improve the residual smear rate by a factor of 4, which is truly an ambitious task, the diameter of the lens drops only to 50 inches. This reminds one of the orbiting astronomical observatory which is to have at its heart a 50-inch diameter telescope. But this system is not expected to be operational until about 1970 and requires the use of a Saturn booster. If, instead, one were to reduce his requirements [redacted] the requirements will be more nearly within reach.

[redacted]

Chart 12 - Required Correction of Image Motion. The relationship given in Chart 11 can be used in a different manner. It is possible to locate, on the graph, existing and proposed systems to determine what degree of correction of image smear is required to attain the design goal. Ground resolution has been removed because each of these systems operates at its own particular altitude and cannot necessarily be scaled to 100 nautical miles. Consequently, the vertical position of each system on the graph does not indicate the quality of ground resolution obtained but rather the angular resolution needed to produce the required quality.

E-6 has a 9-inch diameter lens and a requirement to resolve 10 feet at 2:1 contrast from an altitude of 125 nautical miles. This reduces to an angular resolution of 2.7 arc seconds, notice that the dot representing this system falls above the 2 milliradian per second rate indicating the conservatism of the design.

[redacted]

E-5 has a lens diameter of 13 inches and must attain 1.1 arc second resolution to resolve five feet at 2:1 contrast from 150 nautical miles. The required smear rate is very nearly 1/4 of a milliradian per second or nearly two times better than the 1/2 milliradian per second practical limit. This design requirement is very ambitious, especially when it is considered that the curves represented here are in their present location because of forced processing which did not exist on SO-132 type film at the time when E-5 was proposed and built. [redacted]

It should be remembered here that there are small variations in lens transmission, filtration, and exposure, but for the systems that have been described here, those effects will be very small on Chart 12.

Chart 13 - Minimum Diameter F-Number Focal Length for a Given Resolution and Smear Rate for SO 132 Film.

If a specific film is chosen it is possible to include on the graph of angular resolution versus lens diameter, lines describing the optimum focal length and f-number. This has been done for SO 132 film on Chart 13. One should remember that this is based on lenses which approach the diffraction of an on-axis similar to those described on Chart 4. There is one obvious limit and that is f/.5, the theoretical limit for the f-number of an aplanatic lens. Obviously the lines on Chart 13 are not in accord with our present capability of lens design. There are no existing lenses of f/.5 relative aperture and with a field of view which is sufficiently large for practical use in aerial photography. Therefore, it is necessary to show the loss in resolution as a result of aberrations of lenses which are beyond the state of the art in relative aperture. This is done in Chart 14.

Chart 14 - Optimum Diameter in F-Number for Lenses with Expected Aberrations, SO 132 Film.

On Chart 14 the lines of constant f-number are curved to indicate that lens aberrations become a severe limit to the ground resolution that can be obtained. As a result the lens is less efficient from the standpoint of obtaining a given resolution f a given lens diameter. For example, [redacted]

[redacted]

[redacted] A considerably larger diameter would be necessary and the photographic system would operate far short of the diffraction limit.

The effects of aberrations can be illustrated by drawing a boundary line beyond which it becomes very difficult to design lenses approaching the diffraction limit. This boundary is drawn in red on Chart 14. Again one must realize that such a boundary is neither sharply defined nor can it be represented precisely by a straight line. However, the data that was used to locate this line indicates that the boundary is approximately correct and large departures to the right of this line are well outside of what has been accomplished to date.

Therefore, there are two boundaries, one which is represented by the 1/2 milliradian per second practical limit of smear, and one which describes our limitation in designing lenses. Unfortunately the only region of practical operation lies in the narrow V above the smear limit and to the left of the lens quality line. [redacted]

However, the choice of the film may be an artificial restriction and as can be remembered from Chart 8, coarser grain films of higher speed yield the same angular resolution if the focal length is longer. Since the lens quality boundary was determined by the relative aperture of the lens, it should be possible to move that boundary to the right if coarser grain films than SO 132 are used.

Chart 15 - Limitation of Lens Quality on Optimum Diameter. The displacement of the lens quality boundary caused by coarser grain films than SO 132 is indicated on Chart 15. Notice that it now becomes possible to design and operate a system resolving [redacted] If the coverage is to be relatively great, the amount of the film that must be carried is enormous.

Therefore, one can conclude that if the resolution is to be improved below [redacted] it is essential to expose on faster and faster films at the expense of coarser grain, larger image scale, and greater film weight. As a result the system size as one progresses from [redacted]

[redacted] rows much more rapidly than would first be expected and the weight penalty for placing such an enormous system in orbit is extremely great.

Chart 16 - Width of Ground Coverage versus Ground Resolution. The data on image quality versus quantity for lens systems given on Chart 4 is repeated in abbreviated form on Chart 16. As mentioned earlier, better ground resolution can be obtained only

[redacted]

to insure target acquisition. This decision is very fundamental and the choice of camera types has a great influence on the resolution that can be obtained with a given weight limit.

Chart 17 - Weight of Optics versus Lens Aperture.

It was stated previously that the weight of a lens is primarily a function of its diameter. Lens diameter versus weight is plotted in Chart 17 and the data does indicate a smooth curve relating these two factors. As would be expected, the optics for a panoramic system are somewhat heavier than that of a strip system containing a single lens, consequently a second line is drawn for panoramic systems. Note that in the region from about 10 inches diameter and upward, the increase in lens weight is proportional to approximately the square of the increase in diameter. [redacted] considerably in excess of one ton.

Chart 18 - Film Weight versus Ground Resolution.

There is a very simple relationship between ground resolution, film resolution, and amount of coverage. This is illustrated in Chart 18. One hundred percent coverage is defined as all of the Communist countries amounting to approximately ten million square nautical miles. It is assumed here that all photography is in stereo requiring at least two pictures of each area and that one-third of the weight of film accounts for redundancy and wastage. This loss is not unreasonable when one considers interframe spacing, borders, leader, trailer, and redundancy of coverage especially in northern latitudes. The type film ass here is Estar thin base having a total thickness of about .003 inches.

[redacted]

Chart 19 - Photographic Payload Weight versus Ground Resolution.

If one combines the weight of the film, two lenses, film transport system, structure, electronics, and the many other items whic constitute a photographic payload, he can plot the total weig versus ground resolution for a given amount of coverage. It will be assumed here that the system operates at an altitude of 100 nautical miles and that the smear rate is corrected to the practical limit of 1/2 milliradian per second, any larger smear rate than this will increase the weight. It is obvious that this data is an extrapolation of existing systems. The large numbers of the chart are consequently subject to fairly large errors but they are indicative of system size.

The weight requirement for a ten-foot resolution system covering 100% of the area of interest is about 1,000 pounds. Notice that this is a little less than the number given for E-6, the reason for this is that E-6 has a larger tolerance in smear rate amounting to about 2 1/2 milliradians per second. Since either system would require the use of an Atlas Agena, it seems proper to use a maximum tolerance and utilize the full weight available. It is true that the weight limitations given for the three boosters are not as definitely fixed as indicated in the chart, however, these are the numbers that have been used in the past in designing various systems to be carried by these boosters. There is an increase in weight as the resolution is dropped from ten feet to [redacted] resolution requires a booster approximate to the size of a

Titan III. [redacted] equires an enormous payload, the order of 100 tons.

If there are improvements in the state of the art in the next several years, it should be possible to improve the resolution within a given weight limit. For example, if one assumes that the sensitivity of the film can be increased by a factor of two without any loss in quality, and if one assumes that the smear rate can be reduced to 1/4 of a milliradian per second, that the field of view can be increased by a factor of 1.5 due to an improvement in lens design and if the weight of the film can be reduced by a factor of 2 by a thinner film base then it does become possible to obtain small coverag [redacted] in a Titan III. However, it would be dangerous to assume that this many advances in the state of the art can be made in the near future.

Chart 20 - Items Considered.

As a review, Chart 20 lists the various items that have been considered in the study.

Chart 21 - General Conclusions.

Again, as a review, several things have been concluded from this study.

1. For general purposes the visible portion of the spectrum is still the best. It is wise to include as much of the visible spectrum as can be accommodated by the color correction of the lens. In the more sophisticated systems it is worthwhile to add infrared for supplementary photography.
2. It will be difficult to improve upon 1/2 milliradian per second smear rate unless there is some major change in the technique for correction. Ground resolution is independent of the current films for fixed lens diameter and smear rate. It will be necessary to make an improvement in the state of the art to improve upon the resolution that can be obtained for a fixed input to the camera. Although each film of the current series gives approximately the same result, fine grain film should be utilized for minimum weight and minimum radiation susceptibility.
3. The diameter of the lens is more fundamental in its limitat than is focal length, f-number or any other factor. For a given smear rate and angular resolution a diameter can be determined, however, an optimum focal length exists for a given film and range of smear in illumination conditions.

4. This conclusion about camera type is very fundamental and its effects on the amount of resolution for a given payload weight.

5. From 100 nautical miles there is difficulty in pushing the [redacted] unless one uses faster film than SO 132. Obviously there is a weight penalty in making this change.

5. As a result of this limitation the resolution limit for a Titan III payload with adequate coverage seems to be about [redacted]

Chart 22

There are many areas in which improvements in the state of the art are likely to occur and to affect the quality that was described in this study. On Chart 22, improvements are list in order of likely success. This obviously depends on the opinion of the author. Twice the film speed for the same quality seems like a very likely thing to occur in the next few years. There is also a great deal of work being done on reducing t weight of the optics and a 20% reduction seems in the offing. Greater lens transmission depends on more efficient optical coatings. Work done on this field also seems promising. There has been a gradual improvement in the quality of lens design. Since lenses now approach the diffraction limit, it seems

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advisable to take advantage of this improvement in widening the field of the lens. Although there is a boundary between the visible and infrared imposed because of the change in the brightness relationships in the scene, it is possible to extend the red sensitivity of the film beyond 0.7 microns and thereby increase the amount of available energy. If this increase is modest, the brightness relationships will not be affected adversely. In this study it was assumed that the altitude was 100 nautical miles. Lower altitude gives potentially greater resolution. Reducing the smear rate is a very effective way of improving the potential quality of the system. Although some improvements are more likely than others, any improvement will be worthwhile.

In the second column these improvements are rated in order of the gain in resolution which results. Twice the film speed for the same quality and half the smear rate both yield about a 25% potential improvement in resolution. Lower altitude provides an improvement but only at the cost of reduced coverage. Wider lens field makes panoramic photography easier in that the cycle time is increased. The result is some improvement in image quality. If it becomes possible to reduce the weight of a given optical system, an improvement in resolution can be obtained by increasing the lens diameter to use the weight which has been saved. Further extended red sensitivity and greater lens transmission yield small but usable increases in potential resolution.

Although some of these improvements in resolution may not look very large, the fact that there are many of them implies that a combination of improvements can yield a sizable gain in quality. Therefore, all these improvements, no matter how small, deserve reasonable effort with the hope that the state of the art can be extended and that still better results can be obtained within a given payload weight limit.

OPTICAL REQUIREMENTS

	RECONNAISSANCE	ASTRONOMY *
QUALITY	APPROACHING DIFFRACTION LIMIT 0.1 SECOND FOR 30°	ATMOSPHERIC LIMIT 1/3 TO 1 SEC FOR PHOTOGRAPHY
FIELD	WIDE AS POSSIBLE 1° - 3°	GENERALLY VERY NARROW 0 -.25°
f/No.	RELATIVELY FAST f/3 TO f/7	PRIME FOCUS f/3.3 CASSEGRAIN f/16 COUDE f/30
BAFFLING	REQUIRED BECAUSE OF EXTENDED SOURCE	LESS STRINGENT REQUIREMENTS
TRACK RATE	V/h = .05 RAD/SEC MAX.	7×10^{-5} RADIANS/SECOND
WEIGHT	LOW	UNIMPORTANT

* 200-inch MT. PALOMAR

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~~SPECIAL HANDLING~~
~~SECRET~~

EXISTING LARGE TELESCOPES

- HALE - MT PALOMAR, 200-INCH, f/3.3 AT PRIME FOCUS, FULL FIELD IS 1/2°, WITH ROSS CORRECTORS - ~ 3" = 1/4°
- LICK - MT HAMILTON, 120-INCH, f/5
- HOOKER - MT WILSON, 100-INCH, f/5
- KITT PEAK, 84-INCH, f/2.75
- Mc DONALD - FT DAVIS, TEXAS, 82-INCH, f/4
- FIVE OBSERVATORIES HAVE 72-75 INCH, f/4.8
- SCHMIDT - PALOMAR, 48-INCH, f/2.5, ~7° FIELD
- YERKES - WISCONSIN, 40-INCH f/19
  LARGEST REFRACTOR IN USE

(MOST REFLECTOR TELESCOPES ARE USED AT PRIME, CASSEGRAIN & COUDE FOCUS)

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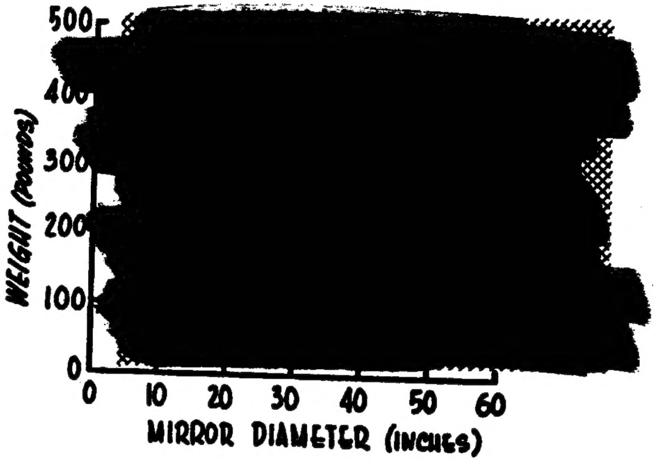
~~SECRET~~
~~SPECIAL HANDLING~~

~~SPECIAL HANDLING~~
~~SECRET~~

MIRROR WEIGHTS
GLASS ALONE

[redacted]



[redacted]

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~~SECRET~~
~~SPECIAL HANDLING~~

~~SPECIAL HANDLING~~
~~SECRET~~

MIRROR WEIGHT
PRIMARY MIRROR - GLASS ALONE

[redacted]

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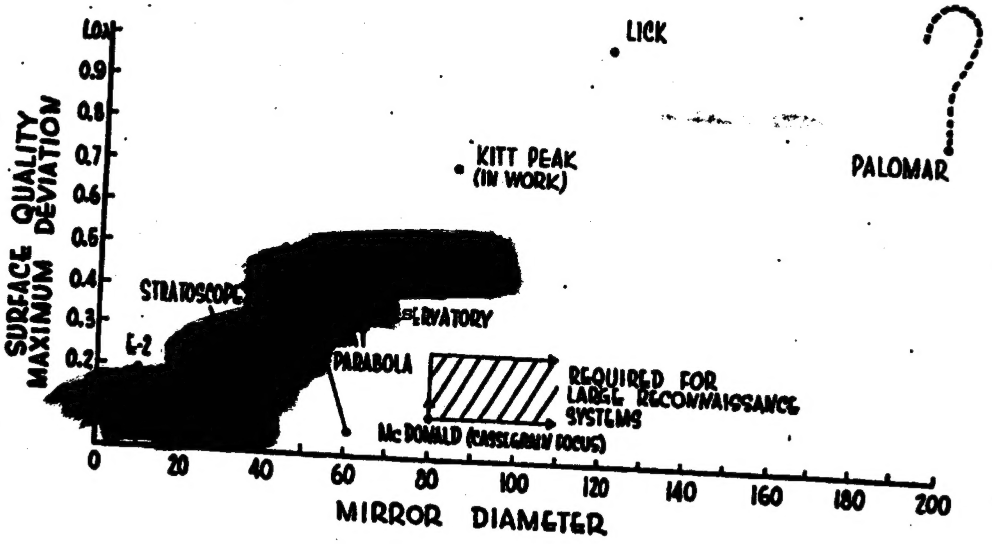
~~SPECIAL HANDLING~~

ROUGH DRAFT

MIRROR SURFACE QUALITY



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~~SECRET~~

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MAY 7 1965

ROUGH DRAFT

MIRROR MATERIALS SELECTION (MID 1965)

MATERIAL	ADVANTAGES	DISADVANTAGES	STATUS
[redacted]	[redacted]	[redacted]	[redacted]
CER-VIT	CAST WITH INTEGRAL CORE & FILLETS (REDUCED STRESS CONCENTRATION) LOW COEFFICIENT	NEW MAT'L. LITTLE EXPERIENCE	FABRICATION TECHNIQUE UNDER DEVELOPMENT
[redacted]	[redacted]	[redacted]	[redacted]
PYROCERAM	LOW COEFFICIENT	SURFACE SCATTER	UNDER DEVELOPMENT FOR LARGE SIZES
BERYLLIUM	HIGH SPECIFIC STIFFNESS HIGH THERMAL CONDUCTIVITY	SURFACE MUST BE COATED FOR POLISHING HIGH COEFFICIENT	ISOSTATIC PRESSING UNDER DEVELOPMENT
SUPER INVAR	LOW COEFFICIENT	SURFACE MUST BE COATED FOR POLISHING DIFFICULT TO FABRICATE	UNDER DEVELOPMENT

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~~SECRET~~
~~SPECIAL HANDLING~~

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